Jet observables in heavy ion collisions
Where to start?
What to look at?

Based in large part on
Review of Jet Measurements in Heavy Ion Collisions
Megan Connors, Christine Nattrass, Rosi Reed, Sevil Salur
https://arxiv.org/abs/1705.01974
But I take responsibility for mistakes

Some of the main points

- Measurement techniques – including biases – need to be taken into account
- Background subtraction should be considered part of the measurement
  - Therefore Jetscape should include the background subtraction algorithms in their implementation of the calculations
- Unfolded measurements might include (unknown) biases from the MC used for the unfolding
  - Amount depends on measurement
  - Some measurements are less sensitive than others
- Not all measurements are necessarily that sensitive to medium properties
  - Of course that is what Jetscape should help us understand!

More about background

- **Our summary of the ATLAS method:**

  We outline the approach in~\cite{Aad:2012vca}. We note that the details of the analysis technique are optimized for each observable. ATLAS measures both calorimeter and track jets. Track jets are reconstructed using charged tracks with \pT~$>$~4~\GeV. The high momentum constituent cut strongly suppresses combinatorial jets, and ATLAS estimates that a maximum of only 4\% of all R~=~0.4 \akT track jet candidates in 0-10\% central \Pb collisions contain a 4 \GeV~background track. For calorimeter jet measurements, ATLAS estimates the average background energy per unit area and the \vtwo using an iterative procedure~\cite{Aad:2012vca}. In the first step, jet candidates with R~=~0.2 are reconstructed. The background energy is estimated using the average energy modulated by the \vtwo calculated in the calorimeters, excluding jet candidates with at least one tower with \ET~$>$~\meanET. Jets from this step with \ET~$>$~25 GeV and track jets with \pT~$>$~10 \GeV are used to calculate a new estimate of the background and a new estimate of \vtwo, excluding all clusters within ΔR~$<$~0.4 of these jets. This new background modulated by the new \vtwo and jets with \ET~$>$~20~GeV were considered for subsequent analysis.Combinatorial jets are further suppressed by an additional requirement that they match a track jet with high momentum (e.g. \pT~$>$~7~\GeV~\cite{Aad:2012vca}) or a high energy cluster (e.g. \ET~$>$~7~GeV~\cite{Aad:2012vca}) in the electromagnetic calorimeter.

  →Strongly biases the result

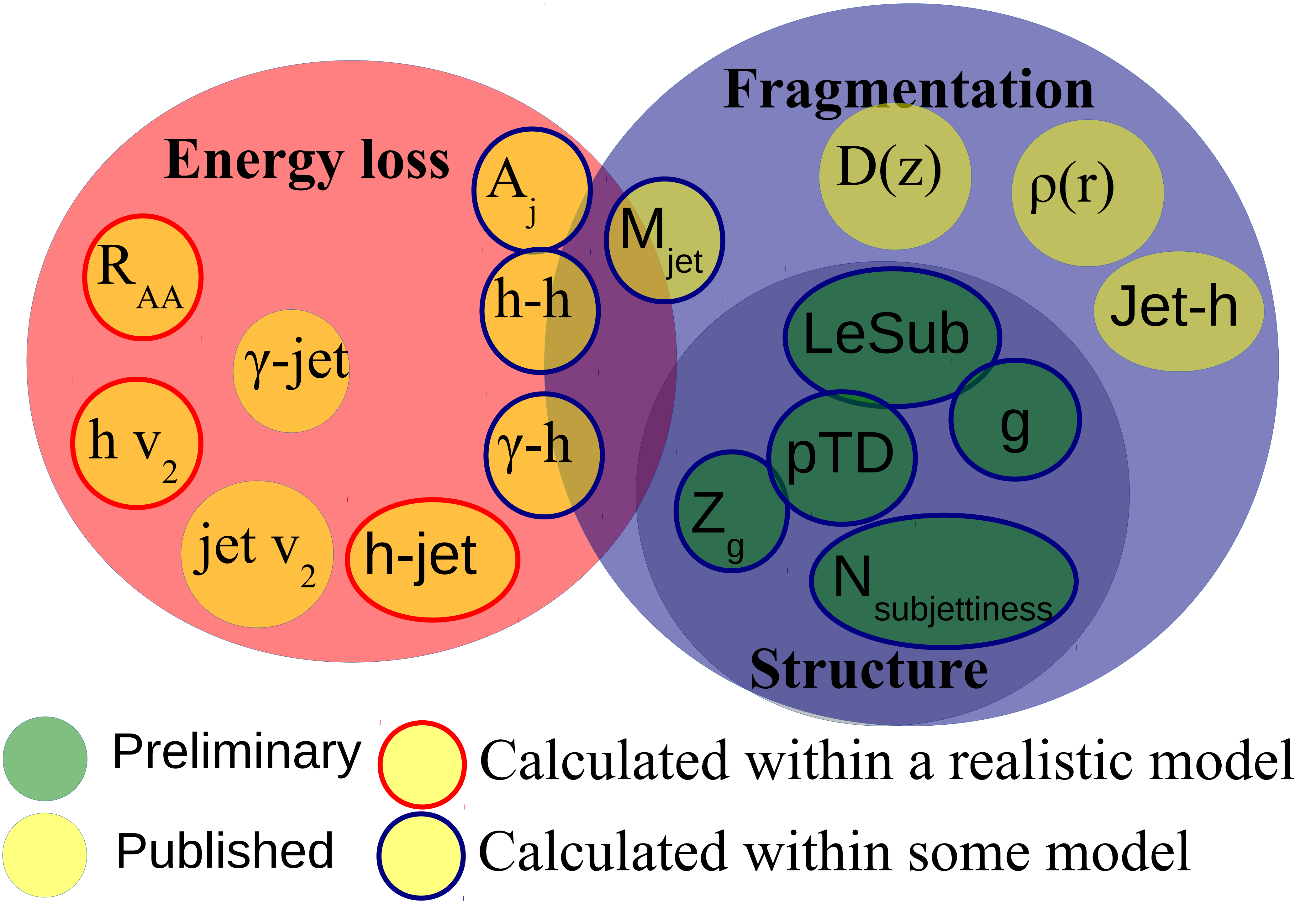
My understanding of goals of this working group

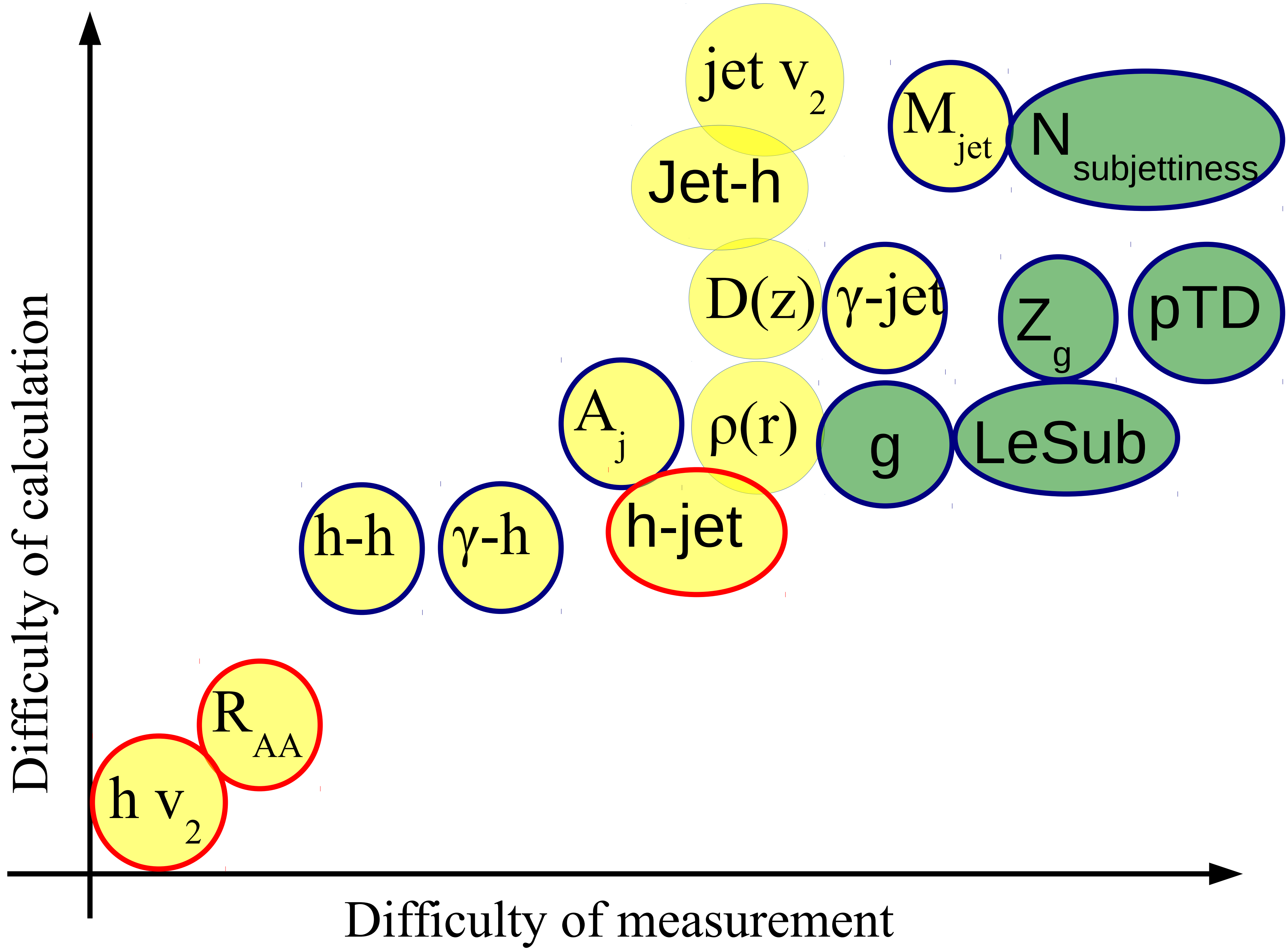
- Observable to develop systematic uncertainty framework
  - More detailed studies will follow but this is what is needed now
- Where to ***start***: straightforward observable
  - Easy to understand the measurement
  - Easy to implement in MC
  - Some reasonable estimate of correlation between systematic uncertainties
  - Should be published already

  → **Single particle R_{AA} or particle spectra,**

  → **Single particle v_2 at high p_T**
- I know some will be disappointed and disagree, but I think this is the most logical place to start

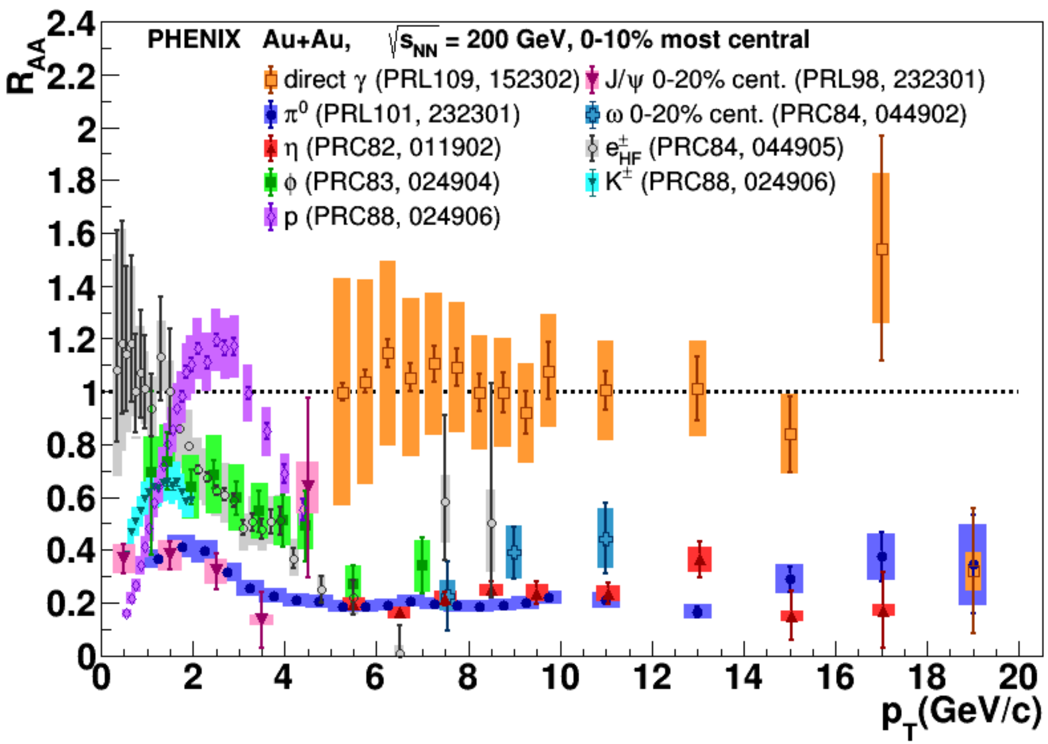
Observables

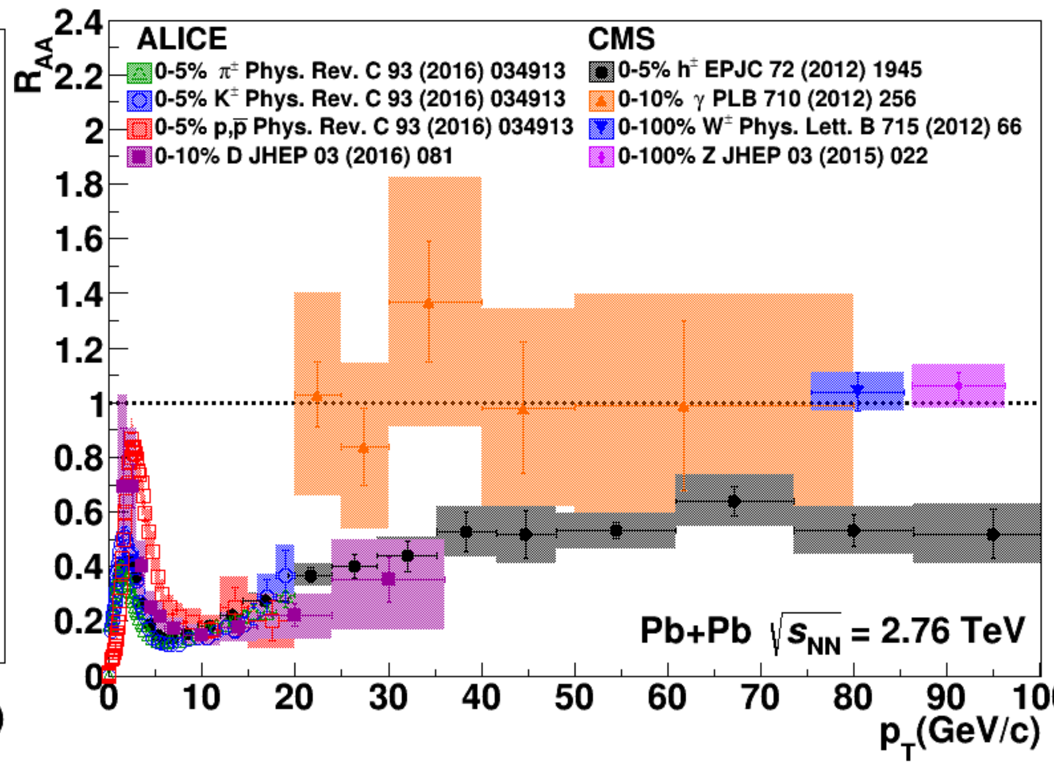




jet v_2
M_{jet}
$N_{subjettiness}$
Jet-h
D(z)
γ-jet
Z_g
pTD
A_j
ρ(r)
g
LeSub
h-h
γ-h
h-jet
R_{AA}
h v_2
Difficulty of calculation
Difficulty of measurement

Single particle R_{AA}





- Good test case for development of uncertainties, correlations between experiments
- Particles available: h, π, p, η, ω, Λ, K, φ, Ω, Ξ, γ, W, Z, c,b→e, D, J/ψ, B

PHENIX classification of types of systematic uncertainties

Phys. Rev. C 77, 064907

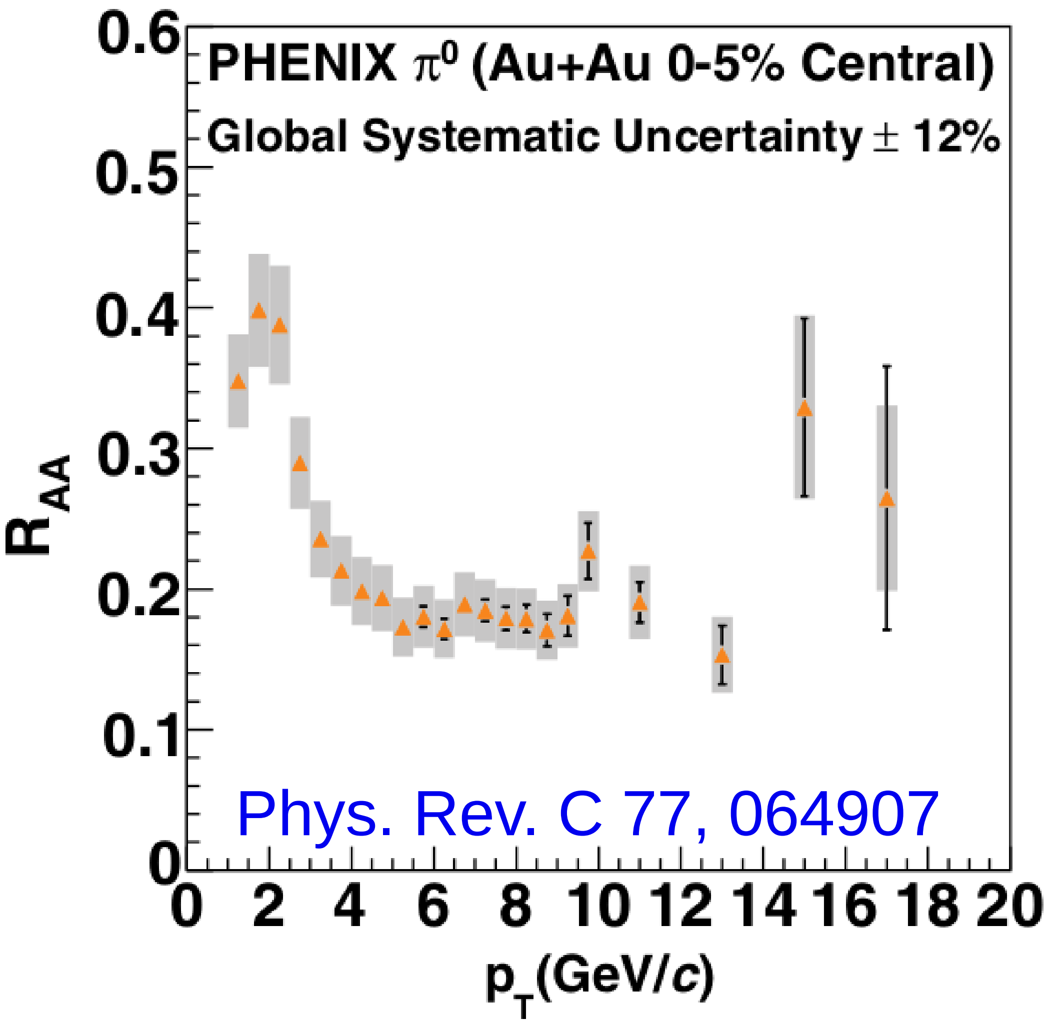
- **Type A:** Uncorrelated point to point (e.g. statistical)
- **Type B:** Correlated point to point
- **Type C:** Scale uncertainties
  - Correlated within one experiment
  - Correlated between several experiments: TAA
- Most PHENIX papers already use this and most uncertainties probably fit into this category fairly well.
- Not sure how uncertainty in correlations between uncertainties are treated

Many thanks to Megan Connors & Mike Tannenbaum for pointing me to this paper!!!

Example: PHENIX R_{AA}

TABLE I. The π^0 nuclear suppression factor R_{AA} as a function of transverse momentum for 0-5% Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The type A, B, and C uncertainties are tabulated for each point.

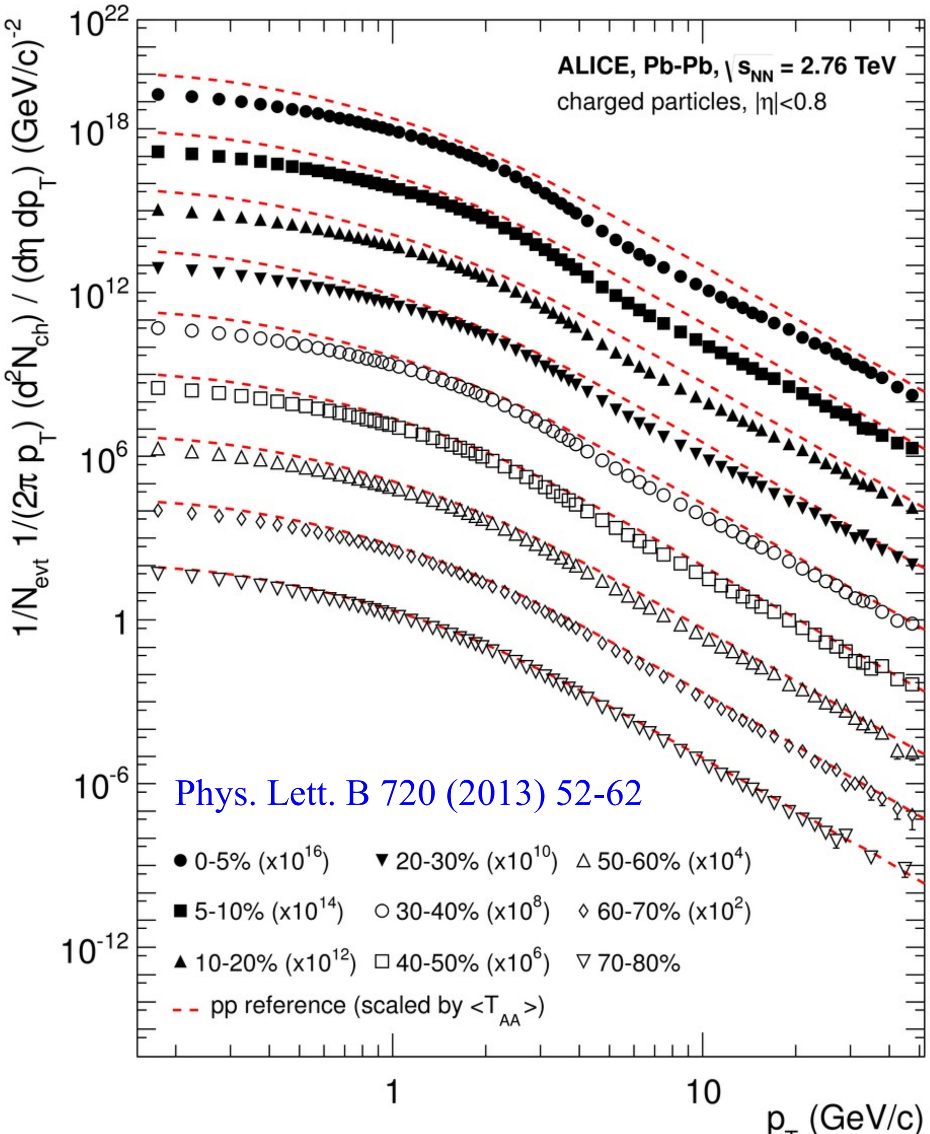
p_T (GeV/c)	R_{AA}	Type A uncertainty	Type B uncertainty	Type C uncertainty
1.25	0.347	±0.007	±0.033	±0.041
1.75	0.398	±0.007	±0.040	±0.047
2.25	0.387	±0.007	±0.042	±0.046
2.75	0.289	±0.006	±0.032	±0.034
3.25	0.235	±0.005	±0.027	±0.028
3.75	0.21	±0.005	±0.024	±0.025
4.25	0.198	±0.005	±0.024	±0.023
4.75	0.193	±0.006	±0.023	±0.023
5.25	0.172	±0.006	±0.021	±0.020
5.75	0.180	±0.007	±0.021	±0.021
6.25	0.171	±0.007	±0.020	±0.020
6.75	0.189	±0.007	±0.022	±0.022
7.25	0.184	±0.008	±0.022	±0.022
7.75	0.179	±0.008	±0.021	±0.021
8.25	0.178	±0.010	±0.021	±0.021
8.75	0.170	±0.011	±0.020	±0.020
9.25	0.180	±0.014	±0.022	±0.021
9.75	0.226	±0.019	±0.028	±0.027
11.00	0.190	±0.014	±0.026	±0.022
13.00	0.153	±0.020	±0.027	±0.018
15.00	0.329	±0.063	±0.065	±0.039
17.00	0.264	±0.093	±0.065	±0.031



- Great example for development of software because the uncertainties are already broken down

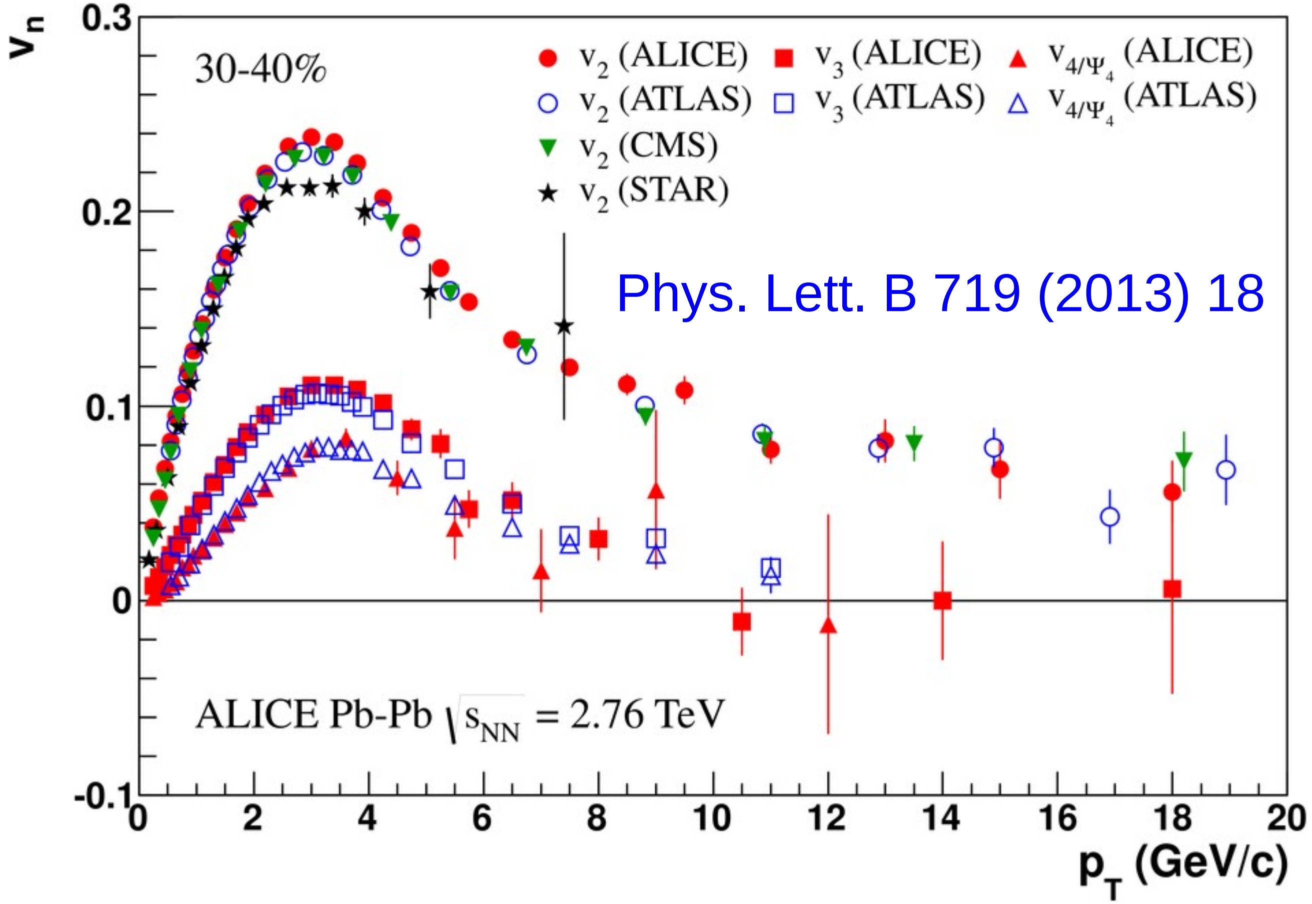
Example: ALICE R_{AA}

Centrality class	0–5%	70–80%
Centrality selection	0.4%	6.7%
Event selection	3.2%	3.4%
Track selection	4.1–7.3%	3.6–6.0%
Tracking efficiency	5%	5%
p_T resolution correction	$<1.8\%$	$<3\%$
Material budget	0.9–1.2%	0.5–1.7%
Particle composition	0.6–10%	0.5–7.7%
MC generator	2.5%	1.5%
Secondary particle rejection	$<1\%$	$<1\%$
Total for p_T spectra	8.2–13.5%	10.3–13.4%
Total for pp reference	6.3–18.8%	
pp reference normalization	1.9%	



- This is an approximation, but probably reasonable. It would take more information than is available in the paper for a better approximation.

Example: ALICE high p_T v_n

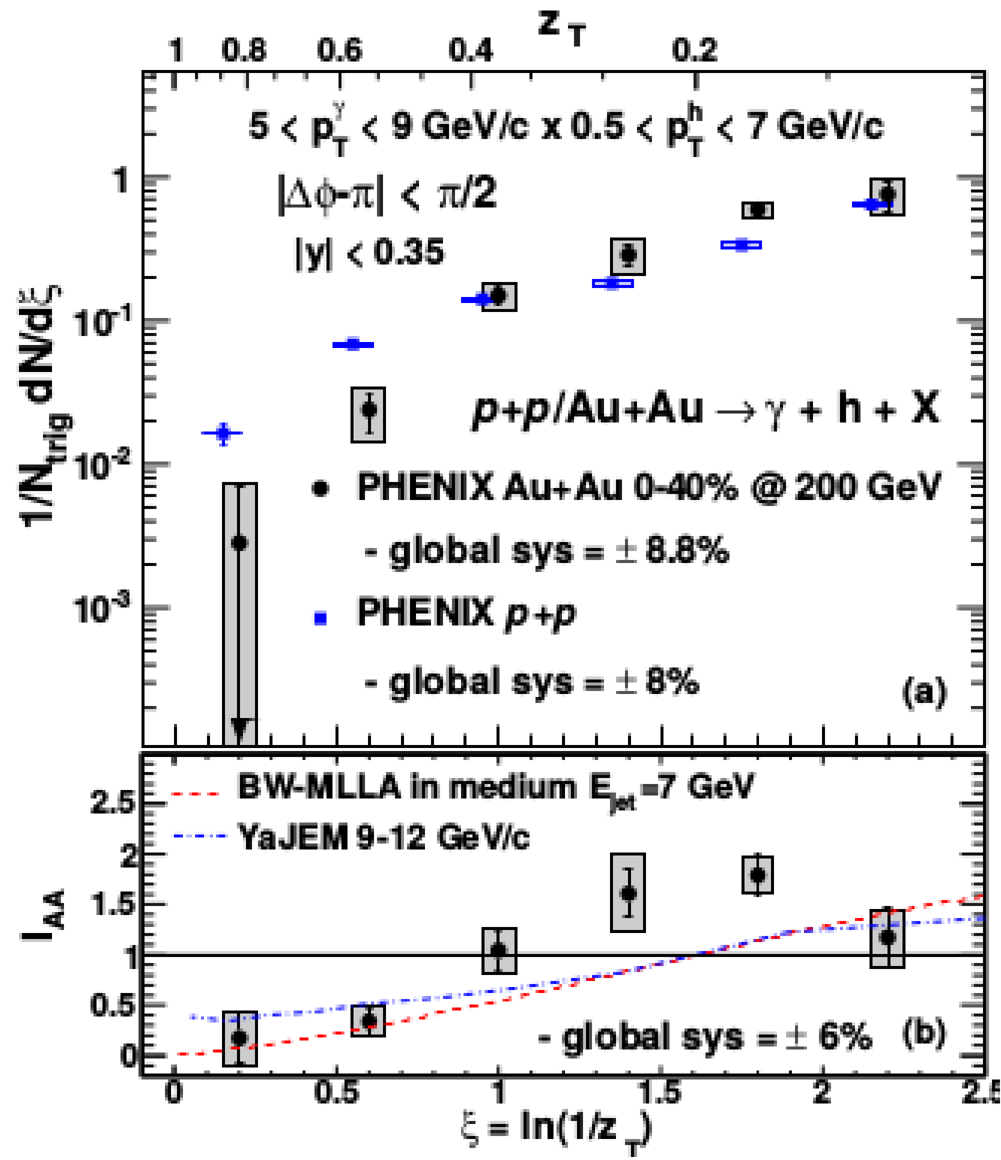


- Systematic uncertainties are probably correlated point to point (**Type B**) to a good approximation
- Observable is clearly defined and uncertainties are small

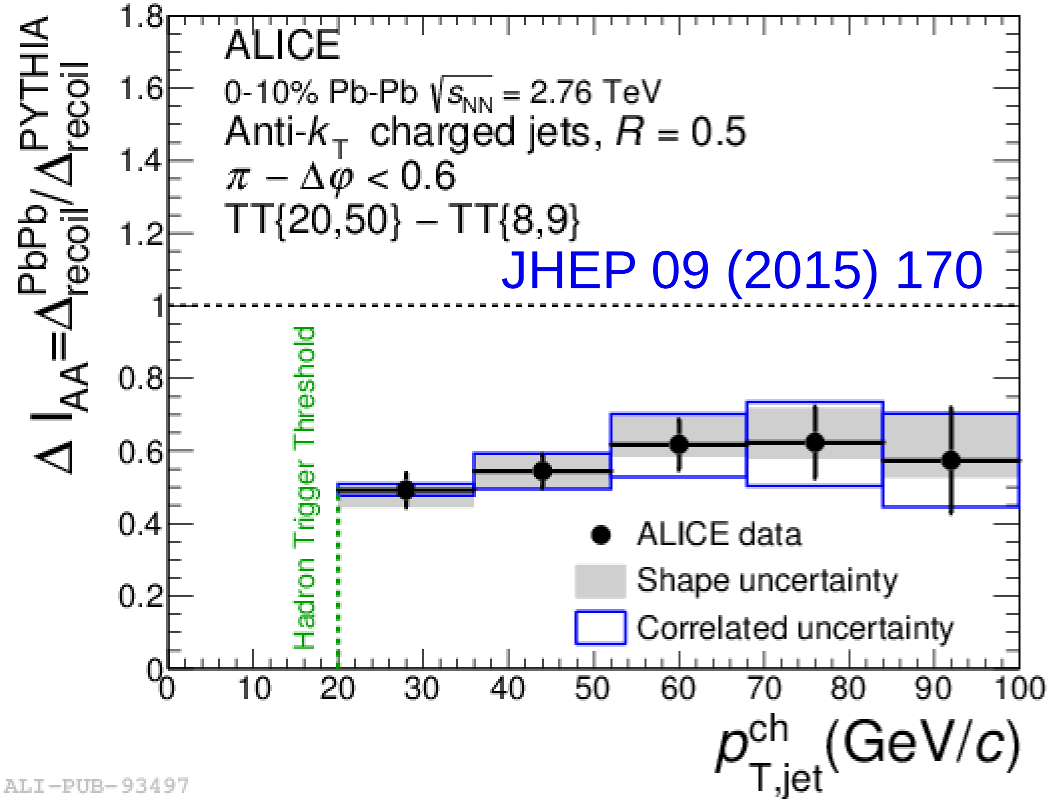
γ-hadron correlations

- **Type A:** statistical uncertainties
- **Type B:** systematic uncertainties on plot
- **Type C:** global systematic on plot
- May be sensitive to background subtraction method (v_1)

Phys. Rev. Lett. 111, 032301 (2013)



Hadron-jet correlations



- Uncertainties already broken into **Type A** (statistical, shape uncertainties) and **Type B** (correlated uncertainty)
- Method is not trivial to implement

Thoughts on other observables

- **Jet R_{AA}:** Need implementation of experiments' methods
- **A_j:**
  - Only one ATLAS measurement is fully corrected for detector effects and therefore even possible to compare.
  - Unclear if this observable is actually sensitive.
  - Also need to take experimental kinematic cuts into account fully.
- **Dihadron correlations:** don't count them out! Yes there are some methodological problems but application of the techniques to MC is straightforward.
- **Z_g, LeSub, p_T^D, g, $N_{subjettiness}$:** All still preliminary!

Backup

Background: ALICE/STAR

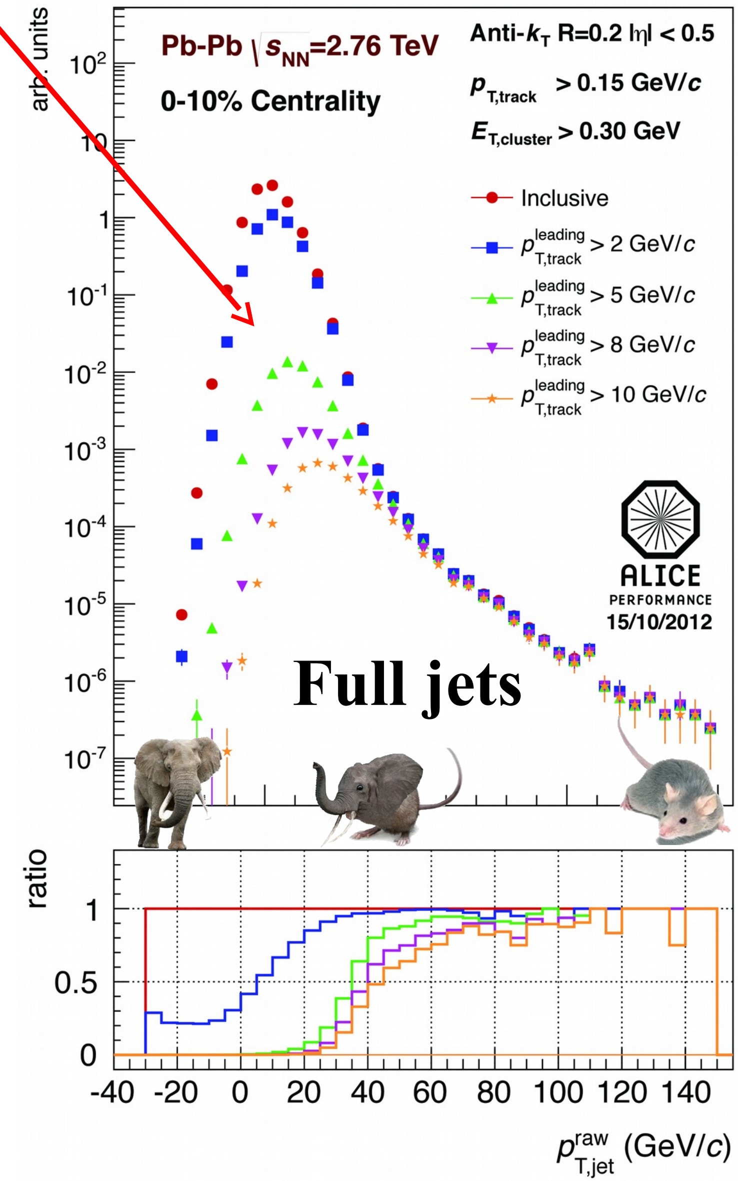
Combinatorial "jets"

- Estimate combinatorial jet contributions and its fluctuations from data
- Require leading track p_T > 5 GeV/c
  - Suppresses combinatorial "jets"
  - Biases fragmentation
- No threshold on constituents
- Limited to small R

Measured spectra:

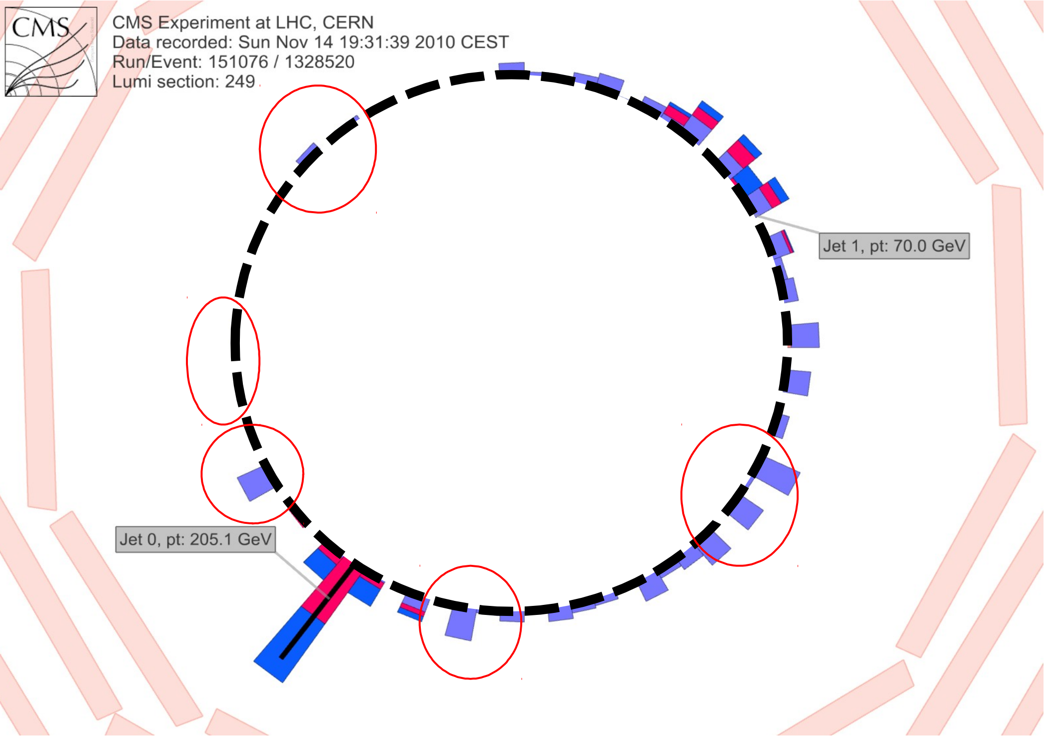
$$p_{T,jet}^{unc} = p_{\mathrm{T,jet}}^{rec} - \rho A$$

Where $p_{\mathrm{T,jet}}^{rec}, A$ comes from FastJet anti-k_T algorithm



Background: CMS

Background is estimated
- for each calorimeter ring of constant η
- subtracted before jet finding
- re-iterated after excluding the jets found in the first iteration



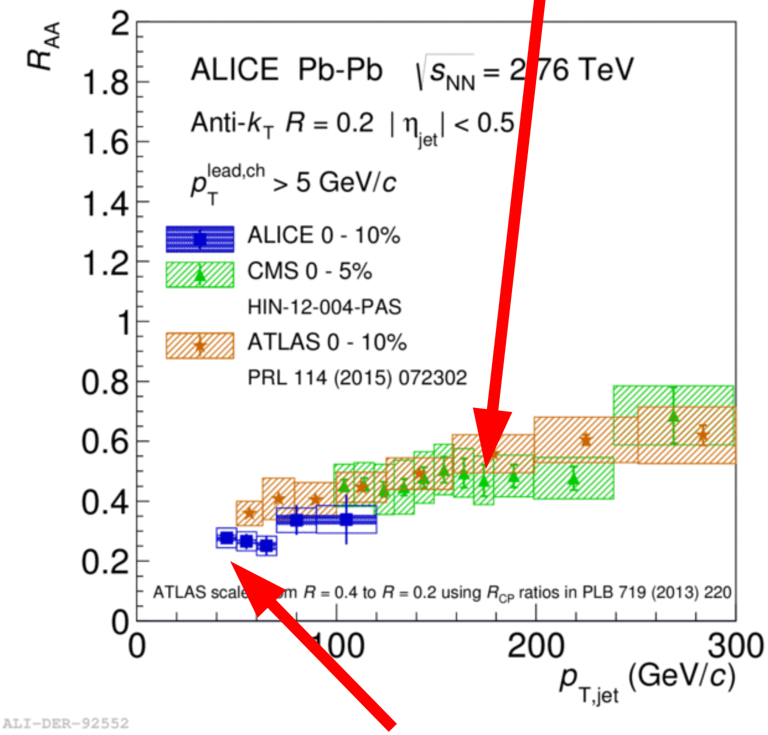
Fake Jets: After the background subtraction, some local fluctuations remain!
Fluctuations will deteriorate the jet resolution in central events.

Sevil Salur 17

Background: ATLAS

- Iterative procedure
  - **Calorimeter jets:** Reconstruct jets with R=0.2. v_2 modulated <Bkgd> estimated by energy in calorimeters excluding jets with at least one tower with
    $E_{tower} > \langle E_{tower} \rangle$
    Track jets: Use tracks with p_T>4 GeV/c
  - Calorimeter jets from above with E>25 GeV and track jets with p_T>10 GeV/c used to estimate background again.
- Calorimeter tracks matching one track with p_T>7 GeV/c or containing a high energy cluster E >7 GeV are used for analysis down to E_{jet} = 20 GeV

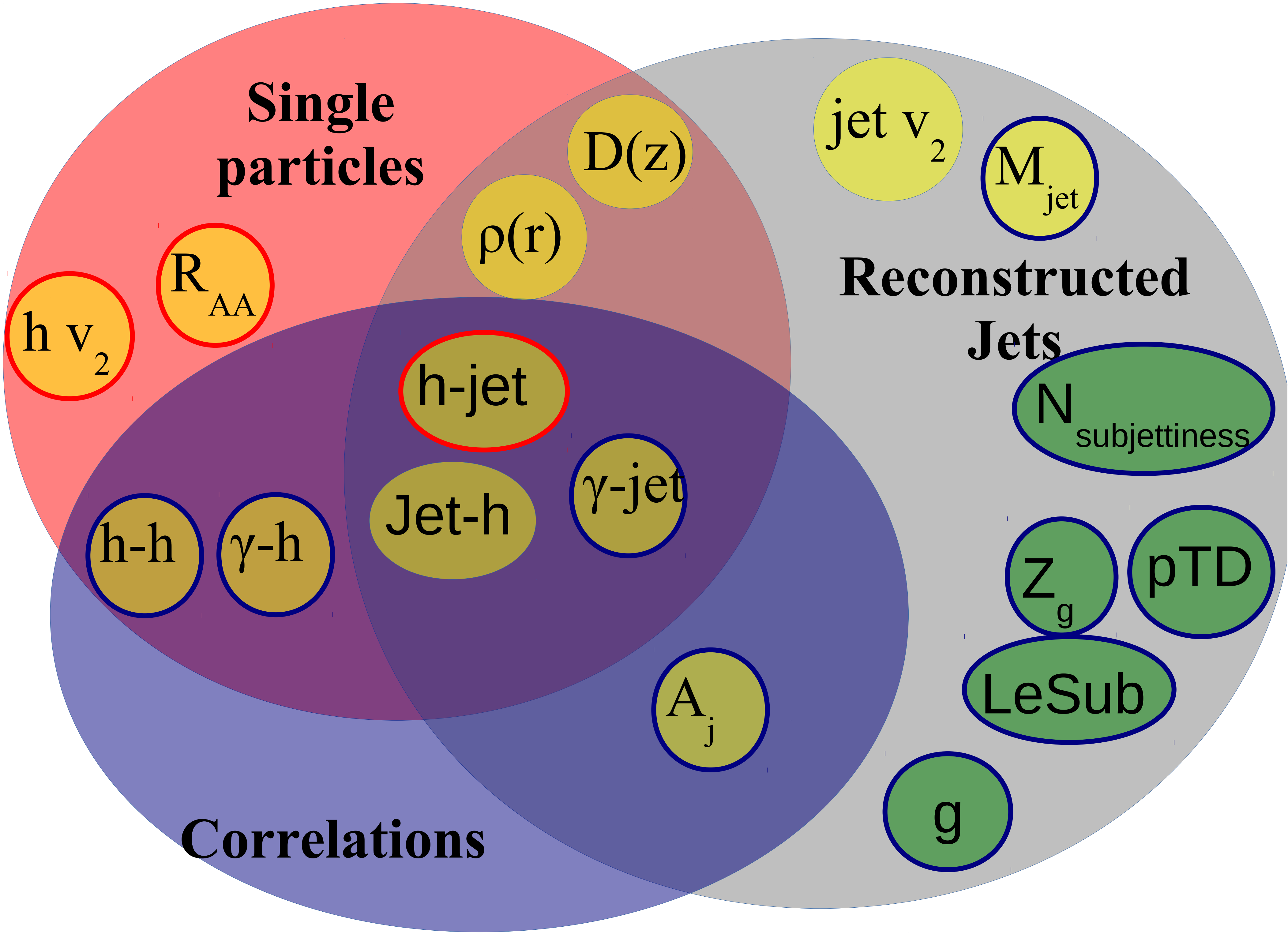
Constituent biases don't matter that much up here



But they do matter down here!

Definitely imposes a bias, especially at 20 GeV!
We should treat that bias as a tool, not a handicap

Phys. Lett. B 719 (2013) 220-241



Single particles
Reconstructed Jets
Correlations
D(z)
ρ(r)
jet v2
Mjet
RAA
h v2
h-jet
Jet-h
γ-jet
h-h
γ-h
Aj
N subjettiness
Zg
pTD
LeSub
g